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Spitzer Space Telescope: Unprecedented Efficiency and Excellent Science on a Limited Budget

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Abstract. The Spitzer Space Telescope completed nearly six years of cryogenic operations in 2009 and in August 2011 began the third year of ‘warm’ science observations. Over 50,000 hours of science have been executed in the first 8 years of the mission. Nearly 40% of the cryogenic mission project budget was devoted to data analysis funding provided directly to the astronomical community. For the warm mission, the observatory was effectively reinvented as a new, scientifically productive mission operating at a substantially lower cost. In this paper we discuss how the design of the science operations, observing modes and observing program for the cryogenic mission led to very high observing efficiencies and maximized the observatory time devoted to science. The philosophy of maximizing science output per dollar has continued in the warm mission. The transition to warm operations has maintained an outstanding science program while reducing the project budget by nearly 70% from the cryogenic mission level.

1. Introduction

The Spitzer Space Telescope, NASA’s Great Observatory for infrared astronomy, was launched 25 August 2003 (Werner et al. 2004). It is the fourth and final element in NASA’s Great Observatories program that includes the Hubble Space Telescope (1990), the Compton Gamma-Ray Observatory (1991-2000), and the Chandra X-Ray Observatory (1999). Until December 2003, Spitzer was known as the Space Infrared Telescope Facility (SIRTF). Spitzer provides sensitivity that is almost three orders of magnitude greater than that of any previous ground-based or space-based infrared observatory. The Observatory was launched with three cryogenically cooled instruments:

- **InfraRed Array Camera (IRAC)**
  – Imaging at 3.6, 4.5, 5.8 and 8.0 microns.
  – PI: Giovanni Fazio, SAO (Fazio et al. 2004)

- **InfraRed Spectrograph (IRS)**
  – Spectroscopy from 5.2 to 38 microns and imaging at 16 and 22 microns.
  – PI: James Houck, Cornell (Houck et al. 2004)

- **Multiband Imaging Photometer for Spitzer (MIPS)**
  – Imaging at 24, 70 and 160 microns and low-resolution spectroscopy from 55-95 microns.
  – PI: George Rieke, Arizona (Rieke et al. 2004)

The cryogenic mission lifetime requirement was two and half years and the observatory exceeded this by more than a factor of two.

After five and half years of science operations the cryogen was depleted on May 15, 2009. During the cryogenic mission the instruments were operated at temperatures of $5-8$K. Upon depletion of the cryogen, the instrument chamber warmed to ~ 27K. At this new equilibrium temperature, the two shortest wavelength bands of the IRAC instrument (3.6 and 4.5 microns) maintain their cryogenic mission performance levels. The longer wavelength IRAC bands (5.8 and 8.0 microns) and all modes of the MIPS and IRS instruments are no longer usable due to the higher background from the warmer telescope. Science operations for the warm mission, operating the IRAC 3.6 and 4.5 micron channels, began July 28, 2009 and can continue through at least 2016 using our new warm operations model. The observatory continues to execute cutting edge science and remains NASA's most efficient community observatory with more than 90% of the time spent executing science observations.

We describe here how the design of the observatory, instruments and operations concepts maximized the observing efficiency and therefore the science output during the limited cryogenic lifetime (see also Gehrz et al. (2007)). In addition, we describe how the warm mission, which on paper has one-sixth of the original capabilities (i.e. half of one instrument) has been reinvented as an entirely new, scientifically productive mission operating at a substantially lower cost. While the number of operating instruments has been reduced, the observatory still operates 24 hours a day, 365 days a year. The annual operations budget, including data analysis support for the astronomical community, has been reduced by two-thirds from an annual level of ~ \$72 million in FY07 to ~ \$22 million today.

2. Early History[1]

The "Shuttle InfraRed Telescope Facility (SIRTF)" was highly recommended in a 1979 National Academy of Sciences report. As proposed, the observatory would have made repeated flights on the Space Shuttle. NASA issued a call for proposals for the mission in 1983 and the instruments were selected in 1984. 1983 also saw the successful launch of the Infrared Astronomical Satellite (IRAS). IRAS performed the first all-sky infrared survey at 12, 25, 60 and 100 microns during a 10-month mission (Neugebauer et al. 1984). NASA did fly an infrared telescope on the Shuttle in 1985 but it experienced substantial problems with contamination from the Shuttle environment. SIRTF kept the acronym but the mission evolved into a free-flying infrared community observatory – the "Space Infrared Telescope Facility." The project faced a major descope in the 1990's and the response to this challenge led to two of Spitzer's most important innovations: the **Warm Launch** and the **Heliocentric Orbit**.

A comparison of the mission design components and costs, before and after the descope, is shown in Table 1 and Figure 1. The warm launch paradigm allows for a substantially smaller cryostat and volume of liquid Helium. For comparison, the IRAS mission lasted 10 months with 510 liters of He while Spitzer lasted 5.5 years with 360 liters. The telescope was launched warm (though the instruments were cold) and passively cooled during the first 75 days of the mission. Active cooling of the mirror

[1]A detailed history of the development of Spitzer can be found in Rieke (2006).

was also provided by Helium venting from the cryostat (see section 3.5). The earth-trailing, solar orbit puts the observatory in an environment far from the heat of the earth. There are no solar or lunar occultations so the thermal environment is extremely stable. Spitzer always keeps the solar panels pointed towards the sun, pointing the telescope boresight no closer than 82.5° towards and no further than 120° away from the sun. These angles define the Operational Pointing Zone (OPZ). Targets at the ecliptic poles are always visible and targets in the ecliptic plane are visible for $\sim$ 40 days, twice per year. Spitzer efficiently slews to targets throughout the OPZ, taking $\approx$ 12 minutes to slew 90°.

Table 1. **Mission Design Evolution**

	Cold launch	**Warm Launch**
Orbit	Near-Earth	Solar, Earth-Trailing
Launch Mass	5700 kg	870 kg
Cryogen Volume	3800 liters	360 liters
Lifetime	5 years	5 years
Launch Vehicle	Titan IV	Delta II
Development Cost	$\sim$ **$2.2 billion**	$\sim$ **$0.67 billion**

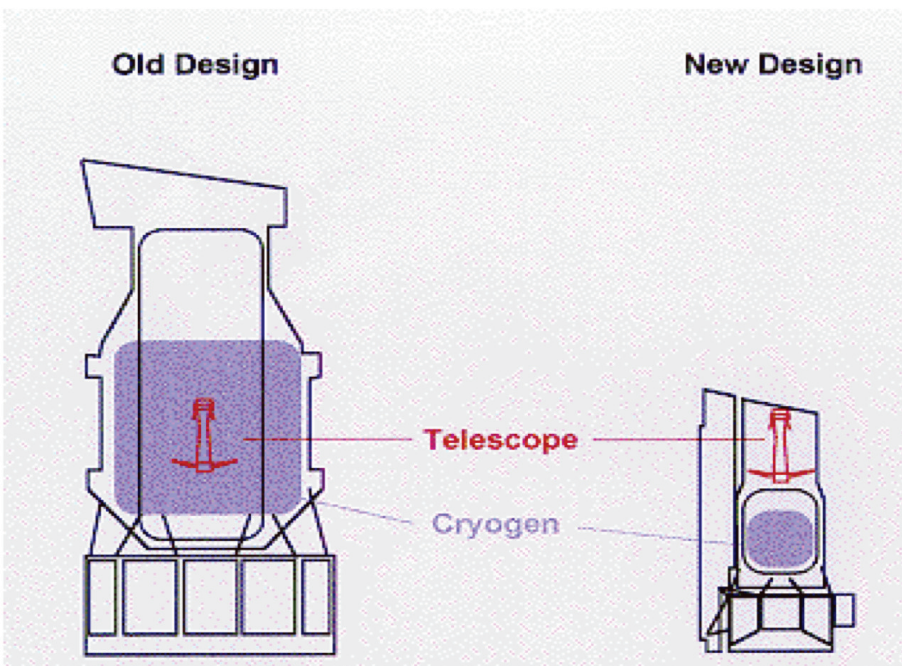

Figure 1. The figure shows graphically the changes in the observatory design, before and after the 1990's descope. The warm launch and heliocentric orbit provide a two-thirds reduction in the development cost without decreasing the expected lifetime or size of the primary mirror.

3. Efficient Operations[2]

To maximize the science output from a limited lifetime mission, observing efficiency is a driving requirement. This influenced the final design of the observatory, instruments and operations concepts. A subset of the specific choices made to this end are highlighted in this section.

3.1. Instruments

The three instruments contained a total of two moving parts: the IRAC shutter and the MIPS scan mirror. The project decided before launch not to utilize the IRAC shutter. Analysis indicated that a failure mode existed where the shutter could fail closed even though it was deemed very unlikely. The other moving part, the MIPS scan mirror, was used successfully throughout the cryogenic mission. The scan mirror enabled "freeze-frame" imaging. While the telescope slewed the scan mirror compensated for the motion, "freezing" the image. The result was extremely efficient mapping of large areas of the sky.

Only one instrument can be operated at a time, so cross-instrument parallel observations were not feasible. There was no science benefit to be gained from operating the instruments in parallel as this would just deplete the cryogen more quickly. However, the instruments were designed so that 'internal parallel' observations were available in most observing modes.

3.2. Observing Modes

The fundamental unit of Spitzer observing is the Astronomical Observing Request (AOR). It is composed of the selected instrument, channel, dithering and mapping parameters chosen from an Astronomical Observation Template (AOT), combined with the targeting information. AOTs provide a limited but powerful set of options for observers to use in crafting their science program. The fact that the combination of options is a finite set gives the observatory a well defined set of modes to calibrate. There are no 'orphan modes', e.g. a grating rarely used or a unique exposure time that requires special calibration. Calibration is robust and special extra calibrations are rarely required.

3.3. Command Generation

Providing estimates of the observing time required is of course essential in the proposal planning phase. The software engine that provides the resource estimates for Spitzer is the same software that eventually builds the command products. This means that the estimates are of extremely high fidelity and makes a one-phase proposal process possible for most programs. The original mission plan was completely a one-phase process but this was relaxed, based on experience, so that very large, complex programs did not need to provide a complete set of AORs with the proposal. Science user support is still required to help investigators craft their programs to meet their science goals but after the proposal selection is complete, most of the programs are fully defined. Spitzer Science Center (SSC) resources can then be devoted to the complex and/or large programs that require more attention.

[2]Substantially more detail about the mission design and operations is available in the Spitzer Telescope Handbook (SSC User Support 2011).

3.4. Observing Cadence and Scheduling

The instruments were scheduled serially in observing campaigns on a ~ 35-day cycle in the order $IRAC \rightarrow MIPS \rightarrow IRS$. Observing in this instrument order facilitated active management of the cryogen (see section 3.5) and made sure that even regions of the sky with the shortest visibility windows (40 days, twice per year) would normally be accessible with all of the instruments. The time allocated to each instrument during this cycle was determined by the selected observing program. There were no external quotas that determined how much time an instrument spent 'on.' Early in the cryogenic mission larger fractions of time were spent with the primarily imaging instruments (MIPS, IRAC) and by the end of the cryogenic mission nearly half the observing time was allocated to the spectrograph (IRS).

The mission is scheduled in one week blocks with a new master sequence controlling the observations for an entire week. The weeks are divided into periods of autonomous operation (PAOs) which are defined as the time between spacecraft contacts. Science observations do not continue during the spacecraft contacts because the observatory orientation is selected to point the high-gain antenna at the earth. During the cryogenic mission the spacecraft contacts were every $12 - 24$ hours and during the warm mission they are every $24 - 48$ hours. Non-science observatory activities are minimal and the uplink of sequences and commands and the downlink of the data occur between the PAOs. This results in $20 - 22$ hours/day for science observations.

3.5. Active Management of the Cryogen

The cryogenic mission lifetime requirement was 2.5 years and the original estimate for the as-built observatory was 4.9 years. The project then developed a plan to actively manage the cryogen rather than just holding the telescope at the lowest required temperature. The MIPS instrument had the most stringent requirements: 5.5K for 160 micron observations and 8.5K for the 24 and 70 micron channels. The telescope was actively cooled by vapor vented from the cryostat. To cool the telescope, heat was introduced into the Helium bath. Based on the observing schedule the heat pulse required to bring the telescope to the required temperature for MIPS was placed into the observing program ahead of the start of the MIPS campaign. In Cycle-2, this was further refined, by introducing 'warm' and 'cold' MIPS campaigns. Programs requiring 160 micron data were segregated into the 'cold' campaigns and the telescope was only lowered to 5.5K for those periods. Implementing these strategies increased the cryogenic mission lifetime to 5.5 years, adding more than 4,000 hours of science to the mission.

3.6. Legacy Science Program

If the Spitzer mission had only lasted the required 2.5 years the usual iterative science cycle of $propose \rightarrow observe \rightarrow analyze \rightarrow publish \rightarrow interpret \rightarrow proposeagain$ would have been too lengthy to follow-up the exciting discoveries expected from opening up an entire new parameter space in sensitivity, efficiency and sky coverage. The Spitzer Project and its community-based advisory group at the time - the Community Task Force - formulated a unique and innovative program that sought to establish an early and long-lasting heritage: the Spitzer Legacy Science Program. The program was motivated by a desire to enable major science observing projects early in the Spitzer mission, with the goal of creating a substantial and coherent database of archived observations that could be used by the broad astronomical community. Legacy Science projects were distinguished by the following fundamental principles:

1. They are large and coherent science projects, not reproducible by any reasonable number or combination of smaller General Observer investigations;

2. They are projects of general and lasting importance to the broad astronomical community with the Spitzer observational data yielding a substantial and coherent database; and

3. They are projects whose raw and pipeline-processed data enter the public domain immediately upon SSC processing and validation, thereby enabling timely and effective opportunities for follow-on observations and for archival research, with both Spitzer and other observatories.

Science topics were not predetermined, and the Legacy Science Program was open to all credible science areas for which Spitzer could make a major contribution. The original selected Spitzer Legacy Science Program was comprised of six projects totaling 3160 hours selected by the SSC in November 2000 following a solicitation of proposals and competitive peer review. They were executed primarily in the first year of the mission, and integrated substantial ancillary data from ground-based observatories and other space-based observatories. Each Legacy Science project developed post-pipeline data products and/or analysis tools that have been delivered to the SSC for wider dissemination to the community. These products, including catalogs and image mosaics, are some of the most popular data available in the Spitzer Heritage Archive (SHA)[3], now at the NASA/IPAC Infrared Science Archive (IRSA). The program proved so popular that Legacy programs were also solicited in Cycles 2 – 5.

4. Community Funding

Throughout the cryogenic mission, approximately 40% of the project budget was provided to the community to support data analysis, archival and theoretical research and the Spitzer Fellowship program. The total project budget was typically \$70 – 75 million/year and of this \$30 – 35 million went to the community. The data analysis funding for observing programs was determined by a formula that took into account

- Total observing time
- Number of Instruments/Modes used
- Complexity of the different observing modes
- Base amount to cover page charges and a computer
- Economies of scale for larger programs
- Creation of enhanced Legacy data products
- Institutional overhead was NOT a factor

[3] `http://sha.ipac.caltech.edu/applications/Spitzer/SHA/`

The SSC did not need to allocate resources to soliciting and reviewing budget proposals. The majority of the funding was issued by the Jet Propulsion Laboratory using a new funding instrument, created for Spitzer, called a Research Support Agreement (RSA). The RSAs are fixed-cost, advance funded contracts that look like grants. They have a very low overhead to issue ($< 5\%$) and the only deliverable is a final report. They are typically issued with a 3-year period of performance.

Data analysis funding was issued at the start of the observing cycle. We therefore did not need to monitor whether a program had started executing before issuing the funding. This was feasible due to the reliability of Spitzer. Funding was not issued to anyone who didn't eventually receive data.

5. Warm Mission - Reinventing Spitzer

Though the exact date of the cryogen depletion was not known in advance, mid-way through the mission we had confidence that it would last into early 2009. No previous cryogenic mission had estimated cryogen depletion at closer than 5% to the actual date which for the Spitzer mission was +/- three months. While operating a warm mission was always part of the baseline plan for the project, planning began in earnest two and half years prior to the depletion of the cryogen. At that time we were anticipating a plan that resulted in a 50% reduction in the operating cost. It was clear that greater reductions would have to be made in the science operations than the mission operations because the observatory still operates 24 hours a day, even with just one instrument. The only obvious task that changed for mission operations was that we no longer needed to monitor or manage the cryogen. For science operations, support for the MIPS and IRS instruments is no longer required. The MIPS and IRS teams at the SSC comprised less than 20% of the total staffing. Therefore other major changes were required to obtain a substantial reduction in operating costs.

The warm mission had no formal level 1 requirements but we developed principles that we adhered to throughout the planning process.

1. Maximize the scientific return of the mission
   – Spitzer exists to do the highest quality science possible. We did not want to continue operating the observatory if the science program was not first rate.

2. Spitzer is a community observatory.
   – As the fourth of NASA's Great Observatories, Spitzer has always executed a community driven science program. The selected observations are peer-reviewed and recommended by the astronomical community.

3. Minimize the risk to the health and safety of the observatory.
   – Changes in mission operations introduced for the warm mission should not add substantial risk to the health and safety of the observatory.

4. Accept additional risk to science.
   – While we did not want to make changes that risked losing the observatory, we did make changes that could have negative impacts on science. These would be manifested primarily in terms of scheduling efficiency. We accepted reduced mission and science operations staffing levels that would lead to slower recoveries from anomalies, fewer late changes to schedules, fewer high-impact scheduling opportunities and less direct user support.

We held a community workshop in June 2007 and received substantive and specific feedback on how we should move forward with the warm mission (see Storrie-Lombardi & Silbermann 2007). Highlights are listed below:

- The community embraced the concept of Exploration Science programs offering $500 - 2500$ hour proposals.
- We must continue to support small programs.
- Continue to select a community-based program. Don't preselect a 'public' survey.
- No strong opposition was voiced to doing the proposal panel review remotely, thereby saving $\sim$ \$250k per year in review costs.

These recommendations were adopted and savings in many other areas were also identified that have been implemented. The changes made in operations for the warm mission include:

1. Reduced the number of observing programs supported annually from $\sim$ 250 to $\sim$ 60.
2. Changed the panel review portion of the proposal peer review into telecons instead of face-to-face meetings.
3. Project only supports one high-impact scheduling interrupt per year and the request must be made via a Director's Discretionary Time proposal.
4. No late changes to schedules except for observatory health and safety.
5. Add one week to the front-end of the scheduling process at the SSC.
6. Schedule downlink opportunities every 24 hours instead of every 12 hours.
7. Reduced software tools support.
8. Reduced engineering staff for performance analysis and anomaly response.
9. SSC dropped Data Quality Analysis Review.
10. Ended the Spitzer Fellowship Program.
11. Reduced Data Analysis Funding to the Community.
12. Stopped soliciting Archival and Theoretical Research Programs.
13. Reduced SSC Direct User Support Staffing.
14. Halved the SSC Public Affairs/Outreach Staff.

6. Summary

The tables in this section provide summary statistics for the life of the mission including a comparison of the cryogenic and warm phases to date. Table 2 shows a comparison of the mean project staffing levels at the start of science operations, the middle of the cryogen mission, and the current warm mission levels. Table 3 provides comparisons of several quantities, other than staffing, for warm and cryogenic operations. The observatory remains very efficient in terms of the number of hours of science scheduled, but has substantially reduced the number of programs supported. The operating budget has been decreased by $\sim$ 45% and user community funding has been decreased by an order of magnitude. The mean operating cost for each hour of science is < $3000.

Table 2. **Spitzer Project - Mean FTEs / year**

	1 December 2003	FY06-cryo	FY12-warm
Project Offices	15.8	9.0	4.3
Mission Operations	64.7	35.4	18.0
SSC + Outreach	112.5	95.8	32.0
Total	**193.0**	**140.2**	**54.3**
% FTEs compared to 1 Dec 2003		**73%**	**28%**

Table 3. **Mission Phase Comparison Summary**

	Cryogen Operations	Warm Operations
Observing Programs Support Annually	250	60
Mean Science Hours Executed Annually	7250	7800
Operating Budget ($million)	37	18
Community Funding Budget ($million)	35	4
Total Budget ($million)	**72**	**22**
Mean Operating Cost/Hour	**$5,100**	**$2,800**

Figure 2 shows refereed publication statistics as reported by Spitzer, Hubble and Chandra for papers based on data from these observatories. These statistics show that NASA's investment in the Great Observatories program continues to provide an outstanding science return with several hundred new publications per year from each observatory.

Warm Spitzer is executing a rich, diverse science program driven by the imagination of the science community. The Warm Spitzer science addresses the most compelling questions of current day astrophysics, ranging from probing the atmospheric structure of exoplanets to determining when the first galaxies formed. Warm Spitzer, with only two arrays operating, produces a scientific return comparable to that of the cryogenic mission in terms of data volume and number of observations executed. The

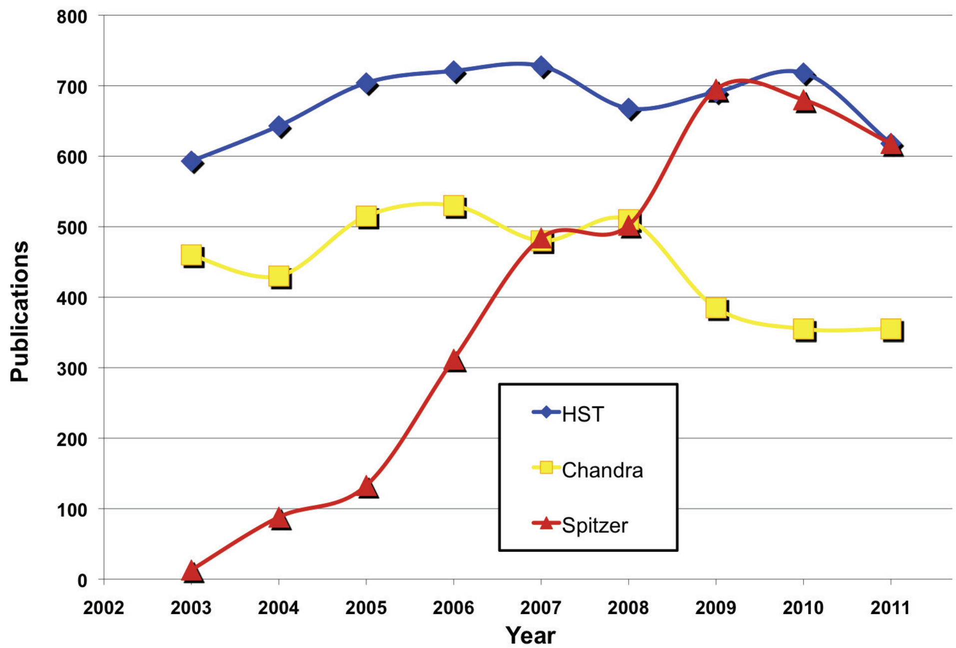

Figure 2. Refereed publication statistics as reported by Spitzer, Hubble and Chandra for papers based on data from these observatories.

project cost has been reduced to one-third of the level during the cryogenic mission and we believe that Spitzer is producing science comparable to multiple Explorer missions.

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